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Land sharing *vs.* land sparing for biodiversity: How agricultural markets make the difference

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Abstract

We show that between intensive and extensive farming, the production method most beneficial to biodiversity depends on the equilibrium of agricultural markets. All other things equal, as long as demand reacts to prices and extensive farming has higher production costs, extensive farming tends to be more beneficial to biodiversity than intensive farming, except when there is a very high degree of convexity between biodiversity and yield. Extensive farming is detrimental to consumers when their surplus is evaluated restrictively, as increasing in quantities consumed, while its effect on agricultural producers is indeterminate. Extensive farming has no straightforward effect on food security, but could decrease the pressure on protected areas. Any increase in demand, notably for animal feed or biofuels, decreases biodiversity, regardless of the production method employed. However, additional demand reinforces the preference for extensive farming, especially in the case of animal feed, for which price elasticity is higher.

Keywords: conservation, farming, biodiversity, land use, markets, welfare

Land sharing *vs.* land sparing for biodiversity:

How agricultural markets make the difference

1. Introduction

A major environmental effect of current agricultural activity is the loss of biodiversity on cultivated land, which raises important concerns because demand for agricultural food and energy products is expected to continue to increase strongly (Alexandratos and Bruinsma, 2012 ; Fritz et al., 2013). The scientific and political debate surrounding this topic has partly centered on the following dilemma: should agriculture be concentrated on intensively farmed land in order to conserve more natural spaces, which are rich in biodiversity, elsewhere (*land sparing*)? Or is it better to favor a more diversified but less productive agricultural approach, i.e. more extensive wildlife-friendly farming that conserves fewer natural spaces (*land sharing*)?

A model by Green et al. (2005) compares the level of biodiversity obtained from intensive high-yield farming and extensive low-yield farming when biodiversity is a decreasing function of yield. For a given production target, the two methods of agriculture lead to the same level of biodiversity when biodiversity is a linear function of yield. Accordingly, when shifting from intensive to extensive farming, the biodiversity gain on previously cultivated land is exactly compensated for by the biodiversity loss on newly cultivated land. If the relation between yield and biodiversity is convex, however, extensive farming leads to a biodiversity loss compared with intensive farming. In this case, shifting to extensive farming leads to a small increase in biodiversity on previously cultivated land, while strongly decreasing biodiversity on newly cultivated land. The opposite result obtains if the relation between biodiversity and yield is concave. According to Green et al., available empirical data from a range of taxa in developing countries support a land sparing strategy. Phalan et al. (2011a), comparing densities of trees and birds for different agricultural intensities in Ghana and India, reach a similar conclusion.

We propose a model that extends that of Green et al. (2005) by adding price as an adjustment mechanism between agricultural supply and demand. We compare the level of biodiversity obtained with each of the two agricultural methods when supply and demand are in equilibrium on the agricultural market. In both aforementioned articles, conclusions are based on the assumption of an identical production target for both agricultural methods. Yet, these two agricultural methods do not necessarily lead to the same market equilibrium. If extensive farming is less profitable per unit of production (therefore a fortiori per unit of land), it can only reach the same production level as intensive farming if farmers receive a higher price, and when the price is higher, demand adjusts downwards. Therefore, we extend the model by making prices and production levels the endogenous outcome of the supply and demand equilibrium. The effect on global welfare then depends on the relative weights attached to producer and consumer surplus on the one hand and to better biodiversity conservation in the short and medium term on the other.

With this new model, we find that, even with a convex relation between biodiversity and yield, extensive farming may increase biodiversity compared with intensive farming. The lower profitability of extensive farming leads to a higher market price, and therefore a lower demand and a lower production output than with intensive farming. Consequently, land use either increases less than if the level of production was kept constant, or even decreases in some situations. Shifting to extensive farming is therefore favorable to biodiversity in more cases than if the production level remained unchanged under both agricultural methods. However, this shift to extensive farming has a detrimental effect on the sum of producer and consumer surplus, with consumer surplus necessarily decreasing, while producer surplus may either increase or decrease.

We illustrate this with a one-good partial equilibrium model representing the relations between agricultural production and biodiversity depending on the agricultural method (intensive or extensive). The model is then extended to account for different market outlets: an agricultural plant product used for food, for feed, or for biofuel production.

2. Theoretical framework

We build our model starting with similar assumptions as Green et *al*. (2005), but we introduce market equilibria. Like these authors, we assume that agricultural production is obtained either by intensive or extensive farming, and we examine the alternative effects of each farming method.

2.1. Relation between biodiversity and yield

We assume that intensive farming has a yield $y_i = 1$, while extensive farming has a lower yield $y_e < 1$. Biodiversity conserved per unit of land is represented by a decreasing function of yield $f(y) = 1 - y^{\alpha}$, which may be linear ($\alpha = 1$), convex ($\alpha < 1$) or concave ($\alpha > 1$) (see figure 1). This formulation normalizes biodiversity per land unit on uncultivated natural spaces to 1 ($f(0) = 1$) and biodiversity per unit of intensively farmed land to 0 ($f(1) = 0$).[1]

[Insert Figure 1]

This stylized representation can account for two contrasting agricultural systems: (1) an agro-industrial system based on large farms that are highly motorized and specialized in a few monocultures with a large use of chemical inputs (fertilizers and pesticides); (2) a system of biological or agro-ecological farming, based on small farms with mixed farming and livestock production, that limits the use of chemical inputs by valuing biological synergies between species, but requires more time and labor (for crop rotation and care, breeding, etc.). This extensive farming offers more favorable conditions to local biodiversity, but attains lower yields than intensive farming. For example, yields of organic farming are reported to be 5% to 35% lower than those of conventional intensive farming (Seufert et *al*., 2012).

For simplification, our model retains the assumption made by Green et al. (2005) that any land cultivated with a given farming method has the same yield, y_i for intensive farming, y_e for extensive farming. Thus, it does not take differences in productivity due to soil and climate into account. To differentiate between lands based on productivity would require more complex assumptions on the relation between biodiversity and yield, as low productivity land farmed intensively may have a lower yield than high productivity land farmed extensively, even though it does not necessarily conserve more biodiversity.

1 We could assume a positive level of biodiversity on intensively farmed land, as in Green et al. (2005), without changing the results of the model.

2.2. Agricultural production and land use

We consider a partial equilibrium model with one sector (the agricultural sector) and one country. Production is carried out by perfectly competitive farmers with a linear aggregated supply function. Total land area is normalized to 1. As long as land availability is not exhausted, when farmers use farming method k, we define the inverse supply function as:

(1) $\forall\ q \in [0, y_k]$, $s_k(q) = a_k\, q - b$.

We assume that parameters a_k ($k = i$ ou e) and b are positive. In this case, the price elasticity of supply is lower than 1, which is consistent with elasticities from empirical studies for the majority of agricultural products (Karagiannis and Furtan, 2002).[2] The interval on which this supply function is defined follows from physical limits on land availability: with land of type k, total production cannot exceed y_k ; the quantity supplied remains equal to y_k for any price above $a_k\, y_k$ - b.

Agricultural producer surplus is given by the area between the price and the marginal cost of production, which are represented by the straight supply line in the (q, p) plane (see figure 2a). It is given by the sum of the areas of rectangle ABED, equal to $(a_k\, q - b)\, b/a_k$, and of triangle BCE, equal to $(a_k\, q - b)(q - b/a_k)/2$. Its expression is therefore given by:[3]

(2) $\forall\ q \in [0, y_k]$, $SU^p{}_k(q) = (a_k^2\, q^2 - b^2)/(2\, a_k)$.

[Insert Figure 2]

For more than half a century, most agricultural research efforts have benefitted intensive farming. Markets and public policies tend to favor it, due to the relatively low price of energy and chemical inputs, while failing to integrate, or inadequately integrating,, their negative environmental externalities (see for example Vanloqueren and Baret, 2008 and 2009). Accordingly, we assume that intensive farming has a higher profitability than extensive farming ($SU^p{}_i(q) > SU^p{}_e(q)$). This translates into the relation $a_e > a_i$.

For each farming method, land use is equal to production divided by yield, as long as some land remains available:

(3) $\forall\ q \in [0, y_k]$, $l_k(q) = q/y_k$.

2.3. Total quantity of biodiversity

If land l_k is allocated to crop of type k, the total quantity of biodiversity is given by $l_k\, f(y_k) + (L - l_k)\, f(0)$. Given that $L = 1$ et $f(y) = 1 - y^{\alpha}$, it is written as:

(5) $B_k(l_k) = 1 - l_k\, y^{\alpha}$.

For intensive farming: $y_i = 1$, $B_i(l_i) = 1 - l_i$. For extensive farming, biodiversity depends on the shape of the relation between biodiversity and yield, as shown in table 1. The different possible cases are represented, among which the limit case where land cultivated with extensive farming produces no biodiversity ($\alpha = 0$), and the limit case where farming land extensively does not decrease its biodiversity ($\alpha \to +\infty$).

2 The price elasticity of supply is $(p/q)\ \partial q/\ \partial p = (p/q)/(\partial s_k(q)/\partial q) = (a_k\, q\text{-}b)/(a_k\, q)$. It is lower than 1 if and only if $b > 0$.

3 The interval on which this surplus is defined follows from the physical limits to land availability defined above.

Table 1. Biodiversity depending on the farming method

Farming method	Relation biodiversity-yield : $f(y) = 1 - y^{\alpha}$		Biodiversity $B_k(l_k)$
Intensive ($y_i = 1$)	$f(y) = 0$		$B_i(l_i) = 1 - l_i$
Extensive ($y_e < 1$)	Linear	$\alpha = 1$	$B_e^l(l_e) = 1 - l_e\, y_e$
	Convex	$\alpha = 0$	$\underline{B}_e(l_e) = 1 - l_e$
		$\alpha \in (0, 1)$	between $\underline{B}_e(l_e)$ and $B_e^l(l_e)$
	Concave	$\alpha \to +\infty$	$\overline{B}_e = 1$
		$\alpha \in (1, +\infty)$	between $B_e^l(l_e)$ and $\overline{B}_e$

2.4. Consumers, equilibrium and welfare

We assume that the purchasing behavior of consumers does not integrate biodiversity. Inverse demand is modeled in a classic way, as a linear decreasing function of quantity, with

(6) $d(q) = c - g\, q$.

Consumer surplus is given on figure 2b by the triangle FGH that measures the area between the straight demand line, which represents consumers' willingness to pay, and the equilibrium price. It is given by:

(7) $Su^c(q) = g\, q^2/2$.

We study the equilibrium depending on the farming method, intensive or extensive. Equilibrium is characterized by:

(8) $s_k(q) = d(q)$.

Total welfare is the sum of producer surplus, consumer surplus and the social utility provided by the conservation of biodiversity, denoted by an increasing function U:

(9) $W_k(q) = SU^p{}_k(q) + Su^c(q) + U(B_k(l_k(q)))$.

Throughout the rest of this article, we use the term "total surplus" for the sum of producer and consumer surplus (this total surplus is thus different from total welfare, as it does not include biodiversity).

3. Comparison of agricultural methods with a unique market outlet

3.1. Graphical analysis of two contrasted cases

Among possible equilibria, figure 3 illustrates the case of a perfectly inelastic demand (the quantity demanded does not react to prices), with c and $g \to +\infty$ and $c/g = 2/3$; while figure 4 illustrates the case of a perfectly elastic demand (there exists a price levels for which the quantity demanded is infinite), with $c = 2/3$ and $g = 0$. Figures 3a and 4a represent market equilibria for each agricultural method, with $a_i = 1.5$, $a_e = 2$, $y_e = 0.7$. Figures 3b and 4b represent land use, and figures 3c and 4c, biodiversity.[4]

[4] In these graphics, the straight lines S_k and D are the inverse supply (of slope a_k) and the inverse demand (of slope g) that represent prices as functions of quantities; the straight lines L_i and L_e represent land use as a

With a perfectly inelastic demand, market equilibrium occurs at price p_i^* if only intensive farming is used, and at a higher price p_e^* if only extensive farming is used (figure 3a). To attain the production level $q_i^* = q_e^*$, more land has to be farmed with extensive farming (l_e^*) than with intensive farming (l_i^*) (figure 3b). If the relation between biodiversity and yield is linear, extensive farming produces the same level of biodiversity as intensive farming ($B_e^{l*} = B_i^*$) (figure 3c). It produces less biodiversity if this relation is convex (between $\underline{B}_e^*$ and B_e^{l*}, depending on the degree of convexity), and more biodiversity if this relation is concave (between B_e^{l*} and $\overline{B}_e$, depending on the degree of concavity). These results are identical to those of Green et al. (2005), as our framework is similar to theirs in the case where equilibrium consumption is the same for both agricultural methods, regardless of their respective profitabilities.

[Insert Figure 3]

If demand is perfectly elastic, shifting to extensive farming leaves the price unchanged, decreases the equilibrium production (figure 4a), and increases land use (figure 4b). The straight line $\tilde{B}$ represents a convex relation between biodiversity and yield such that $B_e(l_e^*) = B_i(l_i^*)$, characterized by $\tilde{\alpha} = 0.19$: in equilibrium, both farming methods yield the same level of biodiversity. Biodiversity decreases with the shift to extensive farming if the relation between biodiversity and yield presents a "high" degree of convexity (between $\underline{B}_e^*$ and $\tilde{B}$); it increases if it presents a "low" degree of convexity, is linear or concave (between $\tilde{B}$ and $\overline{B}_e$).

[Insert Figure 4]

The result of Green et al. (2005) no longer holds if we assume that there is no identical production objective for the two agricultural methods, but that production results from the market equilibrium. As long as demand is elastic, equilibrium production is lower with extensive farming than with intensive farming; total biodiversity may therefore be higher with extensive farming even when the relation between biodiversity and yield is convex.

We complete the analysis by considering welfare changes caused by a shift from intensive to extensive farming.

If demand is perfectly inelastic (figure 3), shifting to extensive farming benefits producers (whose global surplus decreases by *EFAB* but increases by $p_e^* p_i^* EC$, with a positive balance), but is detrimental to consumers (whose surplus decreases by $p_e^* p_i^* BC$) and to total surplus (which decreases by *CFAB*).[5] If the relation between biodiversity and yield is concave, welfare decreases less than total surplus, or even increases, thanks to the increase in biodiversity; if, to the contrary, this relation is convex, welfare decreases more than total surplus because of the decrease in biodiversity.

In the case where demand is perfectly inelastic (figure 4), shifting to extensive farming hurts producers (whose surplus decreases by *E'FAB'*), but does not affect consumers. The welfare loss is higher than the loss of producer surplus if the relation between biodiversity and yield is characterized by a high degree of convexity (the biodiversity line is between $\underline{B}_e^*$ and $\tilde{B}$). In the opposite case (the biodiversity line is between $\tilde{B}$ and $\overline{B}_e$), the social utility provided

function of quantities produced (production divided by yield); the straight lines B_i and B_e^l, and the straight line $\underline{B}_e$ coinciding with B_i, represent the inverse of functions $B_i(l_i)$, $B_e^l(l_e)$ and $\underline{B}_e(l_e)$.

5 These changes in surplus correspond to the established result in the literature, whereby a productivity loss is detrimental to consumer surplus and total surplus, but may increase producer surplus if it is accompanied by a price increase because of an inelastic demand (Karagiannis and Furtan, 2002).

by the higher biodiversity level associated with extensive farming alleviates or even cancels out the loss of producer surplus.

3.2. Comparative statics analysis

The previous results, obtained for a perfectly elastic or perfectly inelastic demand, may be extended to the case where demand is imperfectly elastic (the slope of the inverse of the linear demand curve c is positive and finite, price and quantity adjust based on supply and demand). Equilibrium values are given in table 2. We infer proposition 1 from these values.

Table 2. Equilibrium values of the model's variables

Price	$p_k^* = (a_k c - b g)/(a_k + g)$
Agricultural production	$q_k^* = (b + c)/(a_k + g)$
Farmed land	$l_k^* = (b + c)/((a_k + g)y_k)$
Producer surplus	$SU^p{}_k^* = a_k(b + c)^2/(2(a_k + g)^2) - b^2/(2a_k)$
Consumer surplus	$SU^c{}_k^* = g\,(b + c)^2/(2(a_k + g)^2)$
Biodiversity	$B_k^* = 1 - (b + c)y_k^{\alpha - 1}/(a_k + g)$

Note: a_i and a_e are the slopes of the intensive and extensive inverse supply curves, with $a_e > a_i$; b is the opposite of the intercept of the linear supply curve; c and g are the intercept and the slope of the inverse demand curve; $y_i = 1$ is the yield of intensive farming; $y_e < 1$ is the yield of extensive farming; α is the parameter characterizing the degree of concavity or convexity of the relation between biodiversity and yield. All these parameters are positive. A necessary and sufficient condition for equilibrium is $a_k c > b g$: the equilibrium price is positive.

Proposition 1. *Effects of a shift from intensive to extensive farming.*

As long as land availability is not exhausted, under extensive farming:

- Price increases, production decreases, consumer surplus decreases, the sum of consumer and producer surplus decreases.

- Land use, biodiversity and producer surplus may increase or decrease:

- Land use increases if and only if $g + a_i > (g + a_e)\, y_e$,

- Biodiversity increases if and only if $g + a_e > (g + a_i)\, y_e^{\alpha - 1}$ *(or equivalently,* $\alpha > \tilde{\alpha}$, *with* $\tilde{\alpha} = 1 - \ln((a_e + g)/(a_i + g)) / \ln(1/y_e)$*).*

- Producer surplus increases if and only if $(b+c)^2\, [a_i/(a_i+g)^2 - a_e/(a_e+g)^2] > b^2(a_e - a_i)/(a_e\, a_i)$.

It follows that biodiversity necessarily increases with extensive farming if land use decreases.[6] However, one would expect that extensive farming results in an increase in land use, which, according to the above proposition, is the case under the following conditions: demand responds little enough to price (high g), the yield of extensive farming (y_e) is small

[6] Given that $y_e \in (0, 1)$ and $\alpha > 0$, we have $y_e^\alpha < 1$. Land use decreases when $(g + a_e)\, y_e > g + a_i$, which implies $(g + a_e)\, y_e > (g + a_i)\, y_e^\alpha$, which is the condition under which biodiversity increases.

enough compared with the yield of intensive farming (y_i = 1), and/or extensive farming decreases yield and unit production costs so that the yield loss is not fully transmitted on the slope of the inverse supply curve ($a_e/a_i < y_i/y_e$).

When land use increases, biodiversity increases with the shift to extensive farming when the relation between biodiversity and yield is linear or concave ($\alpha \geq 1$).[7] When this relation is convex ($\alpha < 1$), biodiversity may either increase or decrease, depending on the relative values of parameter α, of the yield of extensive farming (y_e), of the inverse demand slope (g) and of the extensive and intensive inverse supply slopes (a_i and a_e). Biodiversity is more likely to increase as quantities demanded respond to prices (low g), as extensive supply responds less to price than intensive supply (a_e far higher than a_i), and when the relation between biodiversity and yield has a low degree of convexity (α close to 1).[8]

Finally, note that there is no intuitive interpretation of the cases where producer surplus increases or decreases.[9]

3.3. Numeric simulations

To provide better insight into these welfare effects, which are partly indeterminate, we simulate them with plausible values of supply and demand elasticities. For these simulations, we concentrate on the case where the shift to extensive farming has an indeterminate effect on biodiversity (it increases land use, and the relation between biodiversity and yield is convex).

In these simulations, we assume that the yield of extensive farming, y_e, is equal to 0.7. Biodiversity per unit of extensively farmed land, $f(y_e)$, is then convex as long as it is smaller than 0.3. Simulations are performed either with 10 possible values for $f(y_e)$, ranging from 0.01 to 0.29, with a constant difference between these values, or for a given value of $f(y_e)$. We consider 9 possible values for price elasticities of intensive supply and demand, which vary from 0.1 to 0.9 in absolute value, in increments of 0.1. This interval comprises most supply and demand elasticities of agricultural plant products classically used in world models of agriculture (see for example FAPRI, 2012). We assume that the equilibrium with intensive farming is always characterized (as in former graphical illustrations) by $p_i^* = 1/2$ and $q_i^* = 2/3$.[10] The extensive inverse supply slope, a_e, by assumption higher than a_i, is smaller than $a_e^L = (g + a_i)/y_e - g$ in the case illustrated here, i.e. where extensive farming increases land use (see proposition 1). In the simulations, the slope is varied between 1.1 a_i and 0.9 a_e^L, in increments of 0.1.[11]

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[7] Given that $a_e > a_i$ and $y_e < 1$, we have $ln((a_e + g)/(a_i + g)) / ln(1/y_e)) > 0$, therefore $\tilde{\alpha} < 1$.

[8] In the case where the relation between biodiversity and yield is convex, given that $y_e \in (0, 1)$ et $\alpha \in [0, 1)$, we have $y_e^{\alpha-1} > 1$, with $y_e^{\alpha-1} \rightarrow 1$ when $\alpha \rightarrow 1$ and $y_e^{\alpha-1} = 1/y_e$ when $\alpha = 0$.

[9] Analogously to Karagiannis and Furtan (2002), who consider an infinitesimal variation of the slope of the supply curve, it is only possible to interpret a necessary condition for an increase in producer surplus. This necessary condition is that the section between square brackets of the left-hand term in the inequality presented in proposition 1 be positive, which is the case if and only if $a_i a_e > g^2$ (the product of the two slopes of inverse supply is higher than the square of the inverse demand slope).

[10] For each simulation, the slopes and intercepts of the inverse intensive supply and demand, b, c, a_i and g, are computed in order to obtain the equilibrium $p_i^* = 1/2$ and $q_i^* = 2/3$, given the supply elasticity, $p_i^*/(a_i q_i^*)$, and the demand elasticity, $-p_i^*/(g q_i^*)$, and given relations $p_i^* = a_i q_i^* - b = c - g q_i^*$.

[11] Depending on simulations, the difference between the highest and lowest values of a_e, 0.9 a_e^L - 1.1 a_i, varies between 0.48 and 4.29 with a mean of 1.34. The 0.1 increment allows obtaining approximately a mean of 13 values of a_e for each value of the supply and demand elasticities in the simulations. At the equilibrium with

Figure 5 shows the distribution of biodiversity gains and losses resulting from the shift to extensive farming. Biodiversity decreases on average by 6% in all simulations, with a standard deviation of 27% (figure 5a). Thus, these simulations show that even in the unfavorable case where the shift to extensive farming increases land use and where the link between biodiversity and yield is convex, biodiversity increases with the shift to extensive farming for an important set of parameter values. This is all the more so when the degree of convexity of the relation between biodiversity and yield is low. Thus, in simulations where biodiversity per unit of extensively farmed land is $f(y_e) = 0.1$, biodiversity decreases by 18% on average with a standard deviation of 17%). With twice more biodiversity per land unit, $f(y_e) = 0.2$, biodiversity increases by 2% on average (with a standard deviation of 5%).

[Insert Figure 5]

Given that biodiversity per land unit, $f(y_e)$, does not affect surplus levels, we set it to a given value in order to compare changes in the different components of welfare. When it equals 0.15 (figure 6), producer surplus increases with the shift to extensive farming in most simulations, and is positively correlated with biodiversity. In addition, simulations bring out a negative correlation between consumer or total surplus on the one hand, and biodiversity on the other.

[Insert Figure 6]

The change in producer surplus is sensitive to the specification chosen for the supply curve shift caused by the change in the agricultural production method; a specification about which economic theory is not informative (as discussed by Alston et al., 1995, pp. 63-64). Instead of a pivotal supply shift (shift with a given intercept, $-b$, and a slope increase from a_i to a_e), appendix 1 presents simulation results under the alternative assumption of a parallel supply shift (increase of the intercept from $- b_i$ to $- b_e$, without a change in the slope a). In these simulations, contrarily to the case where the supply shift is pivotal, the shift to extensive farming is detrimental to producers in the majority of simulations and the positive correlation between producer surplus and biodiversity no longer exists. Therefore, these simulations show that with plausible parameter values, no general result emerges on the alignment of the interests of agricultural producers on the one hand and the preservation of biodiversity on the other.

4. Comparison of agricultural methods, taking market outlets into account

We extend the former analysis by considering an agricultural plant product with three possible outlets, food not including animal products (to which we will refer simply by "food"), denoted by F; animal feed for the production of meat, milk products and eggs (destined for food), denoted by f; and biofuels, denoted by b. Assuming for simplification that these three demands are independent, the inverse demand for each of these three products is:

(10) $d^k(q) = c_k - g_k\, q$, $k = F, f$ or b.

Total demand being the sum of these three demands, the former framework applies with:[12]

(11) $c = (\sum_k c_k/g_k) / (\sum_k 1/g_k)$; $g = 1 / (\sum_k 1/g_k)$, $k = F, f$ or b.

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extensive farming, the extensive supply elasticity varies between 0.11 and 0.97, with a mean of 0.53, in conformity with typical values of supply elasticities.

[12] For each product, the demand function is $D^k(p) = c_k / g_k - p/g_k$. Total demand is therefore $D(p) = (\sum_k c_k / g_k) - (\sum_k 1 / g_k)\, p$; from which we deduce the expression of total inverse demand and the parameters of equation (11).

4.1. Effects of a change in parameters of the demand function

Proposition 2 below is established from the equilibrium values in table 2. It presents the effects of a change in the parameters of the total demand function in equilibrium with intensive or extensive farming.[13] The results of this proposition enlighten the comparison of both agricultural methods when taking the existence of these three possible outlets into account.

Proposition 2. *Effects of a shift in the total demand function*

- Regardless of the agricultural method, in equilibrium, an increase in the size of markets (increase in c leading to a parallel outward shift in demand) increases price, quantities, land use, as well as producer and consumer surplus, but decreases the biodiversity level, without changing the relative advantage one production method has on the other ($\tilde{\alpha}$ unchanged).

- A higher price elasticity of demand (decrease in g) extends the advantage that extensive farming has on intensive farming (decrease in $\tilde{\alpha}$).

Pressure from higher demand is therefore detrimental to biodiversity regardless of the agricultural production method, and does not change the value $\tilde{\alpha}$ for which both agricultural methods lead to the same biodiversity levels. Yet, a higher price elasticity of demand leads, when price increases, to a larger decrease in commercialized quantities during the shift to extensive farming, which widens the set of situations in which extensive farming is more advantageous for biodiversity (by decreasing $\tilde{\alpha}$).

4.2. Food and feed

With the classical assumption that food demand is less price-elastic than feed demand[14], integrating feed amounts to decreasing the slope of the total inverse demand function, which , all other things equal, increases the advantage of extensive farming vis-à-vis biodiversity. This is illustrated in figure 7, where demand, D, is the (horizontal) sum of food demand, $D^F = 2.5 - 5\ q$, and feed demand, $D^f = 1 - 2\ q$, represented on figure 7a (supply functions are identical to those of section 3.1). The shift to extensive farming increases biodiversity but also increases the agricultural price (figure 7b), which mainly decreases the outlet for feed, for which demand is more elastic (with a decrease in consumption from f_i to f_e), and, to a lesser extent, for food (with a decrease in consumption from F_i to F_e) (figure 7a). This analysis extends the argument presented by Angelsen (2010), who shows that a higher yield may increase the non-food consumption, for which demand is more elastic, to the detriment of the more elastic food demand. Extensive farming uses more land in equilibrium (figure 7c), but preserves more biodiversity as long as the biodiversity-yield relation is less convex than that

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[13] This proposition refers to the value $\tilde{\alpha} < 1$ of parameter α defined in proposition 1: intensive farming is more favorable to biodiversity than extensive farming as long as $\alpha < \tilde{\alpha}$; conversely, extensive farming is more favorable to biodiversity when $\alpha > \tilde{\alpha}$.

[14] It is at least the case for plant food products such as rice or bread, and animal food products such as milk or meat; as illustrated, for example, by the values of the elasticities of the USDA database *Demand Elasticities from Literature* (www.ers.usda.gov/data-products/commodity-and-food-elasticities). It is very difficult to estimate price elasticities for agricultural plant products only destined for food or only destined for feed (mainly cereals and oil crops), as each primary agricultural production is usually destined for several uses: most cereals feed humans as well as animals, and more recently ethanol plants; oil crops are used to produce meals for animal feed, oil for human food, and biodiesel.

represented by $\tilde{B}$'(which is characterized by $\tilde{\alpha}' = 0.558$), is linear or is concave (figure 7d). In the extreme case defined above with no feed demand and only food demand D^F, solving the model numerically shows that extensive farming would preserve more biodiversity than intensive farming only if $\tilde{\alpha}$ were higher than 0.792.

[Insert Figure 7]

4.3. Biofuels

Still distinguishing between food and feed outlets, we now consider a third outlet, biofuels. With current policies mandating that biofuels must be blended into fuel (for example, in the United States, in Europe and in Brazil) (HLPE, 2013), biofuel demand reacts very little to prices.[15] It is modeled as $D^b = 4 - 30\ q$ (figure 8a), which shifts total demand outwards (from D_0 to D on figure 8b). In line with the results of proposition 2, this leads to an increase in quantity produced and land use, and a decrease in total biodiversity, whatever the agricultural production method. Extensive farming is more beneficial to biodiversity than intensive farming if the straight biodiversity line is on the right of $\tilde{B}$'', characterized by a slightly higher degree of convexity than in the former case, $\tilde{\alpha}'' = 0.549$. The introduction of biofuels, of which inverse demand has a very high slope, therefore modestly increases the advantage of extensive farming over intensive farming from a biodiversity standpoint. Given that biofuel demand is quasi identical with both agricultural methods, and that extensive farming uses more land than intensive farming to reach this production level, shifting to extensive farming increases land use more strongly than in the previous case where the biofuel outlet was not taken into account (the difference between L_e and L_i is 7% higher). As in the previous case, it mainly decreases the size of the feed market.

[Insert Figure 8]

5. Discussion-Conclusion

We have shown that the agricultural production method most beneficial to biodiversity depends on the equilibrium of agricultural markets. All other things equal, as long as demand reacts to prices and extensive farming is more costly, extensive farming may be more beneficial to biodiversity than intensive farming if the relation between biodiversity and yield does not have a very high degree of convexity. However, shifting to extensive farming decreases consumer surplus as well as the sum of consumer and producer surplus, while its effect on producer surplus is indeterminate.

5.1. Pressure of agriculture on protected areas

Our model formalizes the argument that intensive rather than extensive farming does not necessarily spare as much land as would be desirable for biodiversity preservation, because it may increase yield without a proportional decrease in farmed land. This argument has already been put forward, notably by Matson and Vitousek (2006), Vandermeer and Perfecto (2007), Perfecto and Vandermeer (2010). In our analysis, when demand reacts to

[15] With a mandatory rate of biofuel blending in fuel, demanded quantities decrease slightly when the agricultural price increases, because this price increase leads to an increase in the fuel price and therefore a decrease in demand for fuel (see De Gorter and Just, 2009).

prices, if the relation biodiversity/yield has a sufficiently low degree of convexity, land sparing would keep its advantage only if the increase in production that it triggers could be thwarted by restrictive policies that protect natural spaces.

The importance of setting up such spaces to protect biodiversity in the face of agricultural pressure has been emphasized by Green et al. (2005), Ewers et al. (2009), Phalan et al. (2011b), Balmford et al. (2012). Our model does not integrate this option. Its introduction would make it profitable to increase land use over authorized use with both methods of agricultural production, thereby encroaching upon these protected areas. Moreover, this incentive to impinge would be stronger for intensive farming, which is more profitable, in particular per unit of land. Preventing this encroachment would require either dissuasive coercive measures, with a high social and financial cost of monitoring and enforcement, or financial support to farmers to compensate them for revenue losses caused by protected areas. The ability of public policies to develop either of these options on a large scale may be questioned (on this topic, see Phelps et al., 2013).

5.2. Effects on different types of outlets and on welfare

According to Fischer et al. (2011), Tscharntke et al. (2012) or Balmford et al. (2012), given that no simple relation exists between the global level of agricultural production and world food security, the trade-off between land sparing and land sharing to preserve biodiversity is not directly a question of food security. Our model explains this conclusion in greater detail, by showing that each method of agricultural production may favor different outlets via its effects on market equilibria.

Thus, our model shows that extensive farming could alleviate pressures on land and biodiversity by increasing the agricultural price mainly to the detriment of outlets for feed and, to a lesser extent, for food. These outlets for feed are related to the human demand for animal products (meat, milk and eggs), which exerts more pressure on land as today, on world average, about three calories or vegetal proteins fit for human consumption (mainly cereals and oil crops) are necessary to obtain one calorie of animal protein also fit for human consumption (meat, milk and eggs).[16] Moreover, this ratio tends to increase over time (Paillard et al., 2011, pp. 46, 51), as the higher the demand for animal products, the more profitable it becomes to convert forests or grazing pastures (two important reservoirs of biodiversity) into feed crops, often monocultures of cereals (corn) and oil crops (soybeans).

This increase in food prices resulting from a shift to extensive farming is detrimental to consumers. It would negatively affect poor consumers, especially in developing countries. However, four factors could temper this effect. Firstly, this increase in agricultural prices could benefit a population amongst the poorest in the world: the hundreds of millions of small agricultural producers concentrated in Asia, Africa and Latin America, who now account for the main share of those active in agriculture around the world (Dorin et al., 2013). Secondly, the additional biodiversity resulting from a shift to extensive farming may have a positive effect on yields in the medium term, by improving soil fertility, local climate conditions or pollination. Thirdly, this additional biodiversity could have beneficial effects on the provision of ecosystem services other than those directly associated to yield (for example the control of human disease, water purification and nutrient recycling). These other services are also

[16] This ratio is a world average excluding biomass not edible for humans but edible for animals, such as pastures or fodder crops or crop residues.

associated with the welfare of consumers, notably the poorest ones (ten Brink, 2011). Finally, per capita consumption of animal products is the highest in industrialized countries, and these animal products rely on the highest use of food biomass.[17] A shift to extensive farming would therefore have a stronger impact on consumers in industrialized countries, via animal products which they tend to over-consume to the detriment of their health (cardiovascular and other diseases). Therefore, public policies inciting a shift to extensive farming could complement other policies aimed at influencing consumption patterns, in order to decrease both the overconsumption of animal products and food waste at the production and consumption stages (Paillard et al., 2011).

Unlike feed outlets, as long as biofuel outlets are ensured by public policies mandating their incorporation into fossil fuel, the shift to extensive farming cannot limit them significantly. These policies of mandatory blending therefore lead to a decrease in total biodiversity whatever the method of agricultural farming. This result should be emphasized, as the scientific debate on the environmental effects of biofuels remains largely centered on greenhouse gas emissions (which decrease or increase depending on the case and on whether indirect changes in land use are taken into account); even though their effect on biodiversity, which is much less studied, is doubtlessly negative (see Krausmann et al., 2013).

Our analysis could be extended by distinguishing between different countries, depending on their level of development and their place in the international trade of agricultural products. This would allow for a more precise study, for each type of country, of the effects that a change in the farming method has on the different outlets and on the three components of welfare (producer surplus, consumer surplus and biodiversity). Besides, it would be of interest to model agro-food chains, for example by distinguishing between farmers and industrial input suppliers (chemical fertilizers, pesticides and fossil energy). While a shift to extensive farming has an indeterminate effect on the surplus of agricultural producers in our model, it would negatively affect suppliers of industrial inputs used mainly in intensive farming. Furthermore, the market and welfare effects of our model could be studied in more detail, by taking differences in productivity depending on soils and climates (our model assumes a unique yield for all land) and the price elasticity of yield (we assume that the yields of both farming methods are independent of equilibrium prices) into account.

5.3. Technical progress and ecological intensification

In our model, we assume a static and decreasing relation between biodiversity and yield. In the past, to reduce food prices and avoid famines, and in the context of a low-cost supply of fossil energies, the specialization of agricultural productions (development of a few monocultures) and the intensification of their yield by industrial inputs (chemical fertilizers, pesticides) have occurred to the detriment of numerous environmental goods and services, among which biodiversity (Foley *et* al., 2005). Nowadays, taxing negative externalities related to agriculture could be considered, notably with regards to biodiversity, to encourage the intensification of biological synergies between various vegetal and animal species above and below soil surface, rather than the use of industrial inputs. Such taxation in favor of agro-ecology (Altieri, 1999) or ecological intensification (Bommarco et al., 2013) would increase

[17] In countries with very low revenue, non-food biomass, in particular bush and crop or food residues, are used significantly more for feed, as arable land is mainly cultivated for food. Milk and meat yields are of course much lower, but these animals also provide other services (traction; soil fertilization, fuel or building material with animal faeces).

agricultural production prices, and therefore consumer prices, and would have a negative impact on some operators, such as current suppliers of chemical inputs. Yet, it could eventually generate important welfare gains, by improving soil fertility, local climate conditions, disease or flood control, nutrient recycling and water purification, the revenue of small agricultural producers and, more generally, the health of people and ecosystems. Research and development (R&D) could also support these technical and social innovations by moving in their direction with as much assertiveness and means as it moved, starting from the 1960s, in the direction of the “green revolution” in Asia or the “agricultural modernization” in Europe.

In our model, we did not consider this possible diversified agriculture, highly productive and highly providing of ecosystem services, which largely remains to be designed locally, depending on the peculiarities of each agro-ecosystem (Cunningham et al., 2013). To take it into account in the model would necessitate introducing different relations between biodiversity and yield depending on production methods, i.e. assuming a convex relation for classical intensive agriculture, but a concave one for ecologically intensive agriculture; these convexities and concavities depending on R&D investments in both chains (as represented in Tscharntke et al., 2012, figure 1 p. 54). Evaluating the relation between yield, biodiversity and welfare in both cases, would require looking into the type of biodiversity that should be measured. Biodiversity of agricultural vegetation and of the fauna below and above the ground provides ecosystem services and human welfare, and may likely eventually improve the relation between biodiversity and yield. These properties are far from being borne out for example by solely birds, which are a classical biodiversity indicator. Finally, benefits of specific and genetic diversity should also be taken into account, to extend current approaches limited to the abundance or density of communities.

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Appendix 1. Comparative statics with a parallel supply shift

With a parallel supply shift, the inverse supply function is $s_k(q) = a\,q - b_k$ if farmers use production type k, with a and b_k positive ($k = i$ ou e) and $b_e > b_i$. Producer surplus is $SU^p{}_k(q) = (a^2\,q^2 - b_k^2)/(2\,a)$.

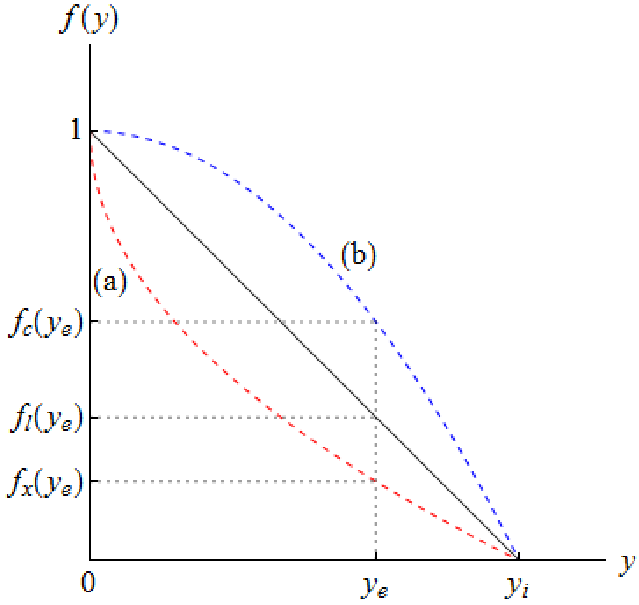
Solving the model with these supply functions, we obtain equilibrium values of variables $p_k^* = (a\,c - b_k\,g)/(a + g)$, $q_k^*=(b_k + c)/(a + g)$, $l_k^*=(b_k + c)/((a + g)y_k)$, $SU^p{}_k^* = a(b_k + c)^2/(2(a + g)^2) - b_k^2/(2a)$, $SU^c{}_k^* =g\,(b_k + c)^2/(2(a + g)^2)$ and $B_k^* = 1 - (b_k + c)(1 - f(y_k))/((a + g)y_k)$. The result of proposition 1 still holds, except for the conditions under which land use, biodiversity and producer surplus increase or decrease. Here, land use increases if and only if $c + b_e > (c + b_i)\,y_e$; biodiversity increases if and only if $(c + b_i)\,y_e > (c + b_e)\,(1- f(y_e))$; producers surplus increases if and only if $(2a+g)\,(b_e + b_i)\,g > 2a^2c$.

In simulations, as with a pivotal supply shift, yield y_e is set to 0.7, $f(y_e)$ varies between 0.01 and 0.29 with ten possible values, and in the equilibrium with intensive farming each price elasticity of supply or demand varies between 0.1 and 0.9 in absolute value, with 9 possible values. In each simulation, slopes and intercepts of intensive inverse supply and inverse demand, a, g, b_i et c, are computed so that the equilibrium with intensive farming is characterized by $p_i^* = 1/2$ and $q_i^* = 2/3$. Land use increases with extensive farming as long as the intercept of the extensive inverse supply, b_e, is higher than the value $b_e^L = (c + b_i)\,y_e - c$. In simulations, b_e varies between 1.1 b_e^L and 0.9 b_i, by increments of 0.1 to ensure on average approximately 8 values of b_e for each value of a_i and g (depending on simulations, the difference between the highest and lowest values, 0.9 b_i - 1.1 b_e^L, varies between 0.36 and 2.4 with a mean of 0.82). In total 7090 simulations are run (with 709 simulations for each value of $f(y_e)$).

[Insert Figure A1]

[Insert Figure A2]

Figure 1. Relation between biodiversity and yield



Note: Biodiversity is a decreasing function of yield, which may be linear (plain line, $f(y_e) = 1 - y$), convex (dashed curve a, here in the case of $f(y)=1-y^{1/2}$) or concave (dashed curve b, here in the case of $f(y)=1-y^2$).

Figure 2. Producer and consumer surplus

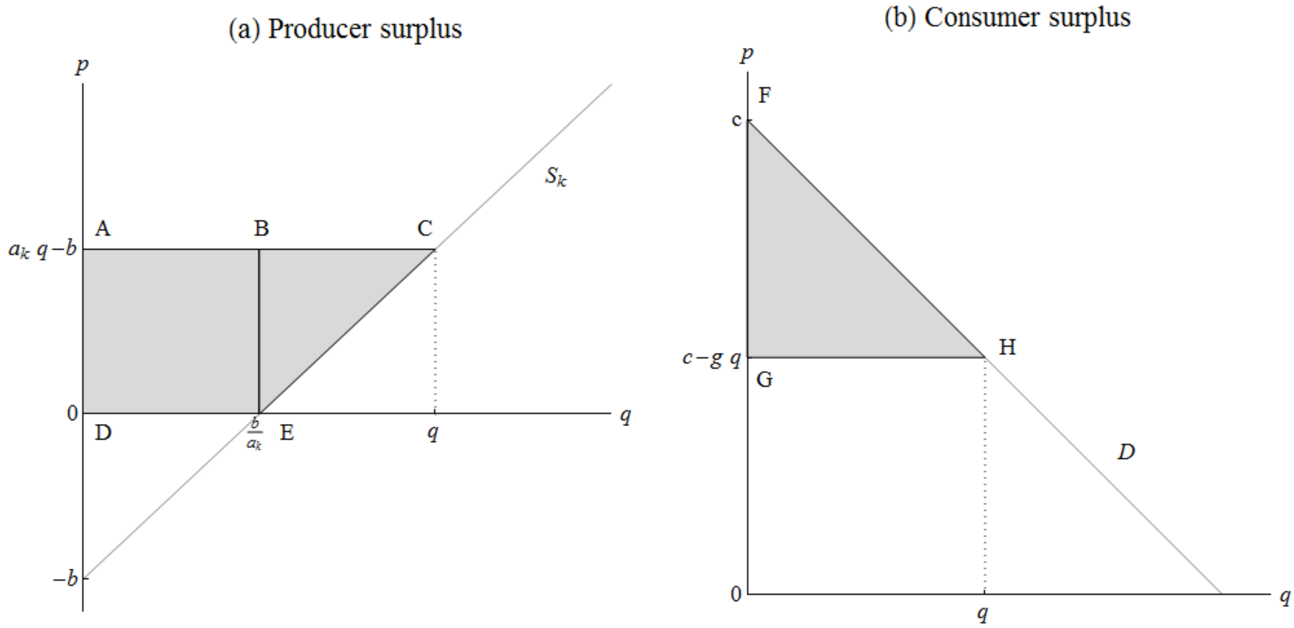


Figure 3. Equilibrium with a perfectly inelastic demand

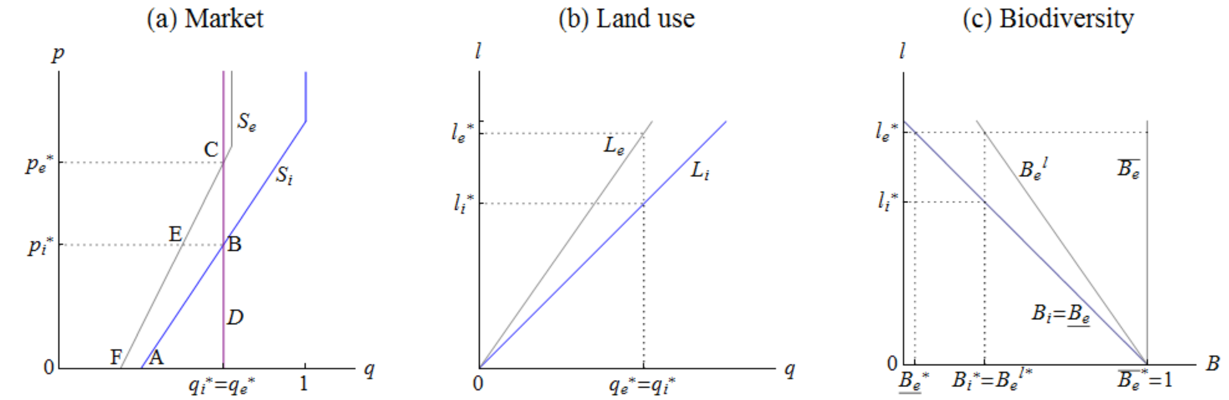


Figure 4. Equilibrium with a perfectly elastic demand

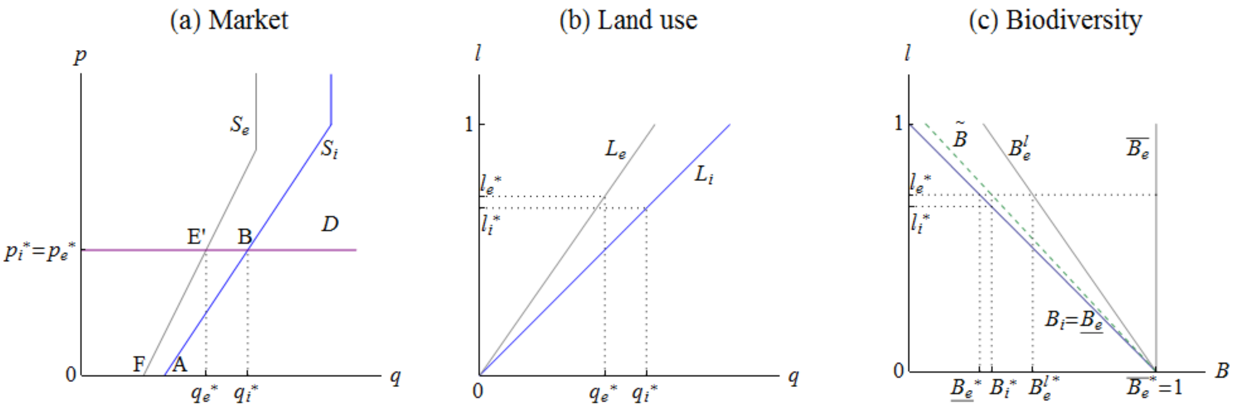
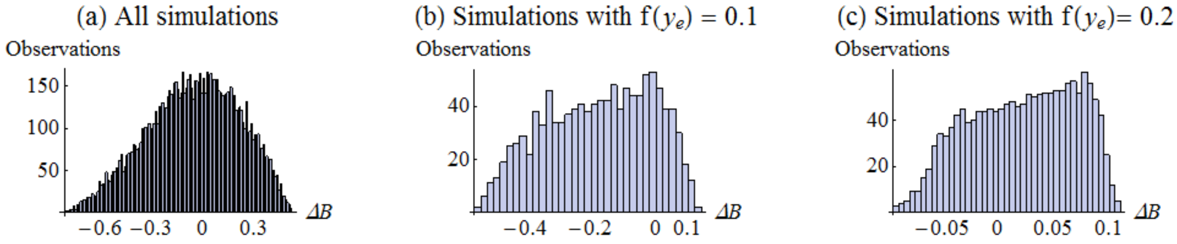
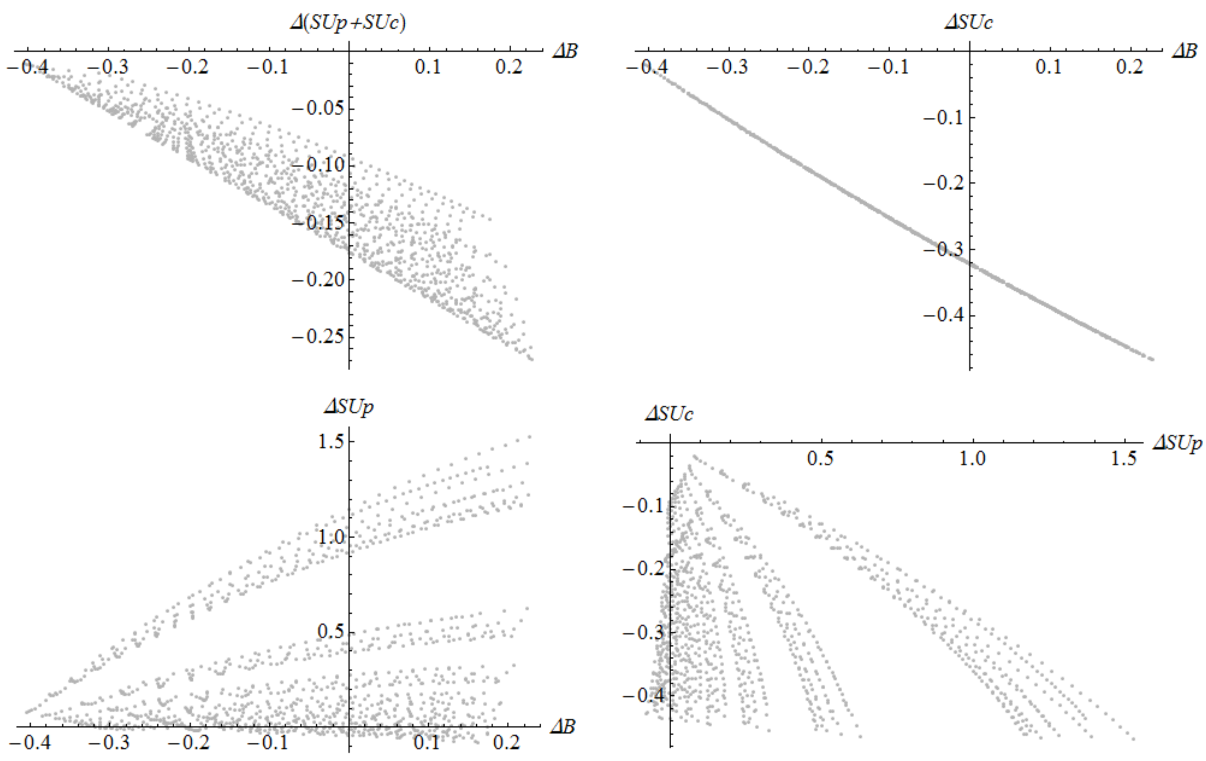


Figure 5. Effects on biodiversity of a shift from intensive to extensive farming



Note: In this figure, ΔB represents the percent variation of biodiversity resulting from a shift from intensive to extensive farming ($\Delta B = (B_e - B_i)/B_i$). Mean *m* and standard deviation *s* of the biodiversity change ΔB are: (a) in all simulations: *m* = - 8%, *s* = 28%; (b) in simulations where $f(y_e) = 0.1$: *m* = - 20%, *s* = 18% ; (b) in simulations where $f(y_e) = 0.2$: *m* = 2%, *s* = 5%.

Figure 6. Welfare effects of a shift from intensive to extensive farming ($f(y_e) = 0.15$)



Note: In this figure, $\Delta(Su_p + Su_c)$, ΔB, ΔSu_c and ΔSu_p represent respectively the percent variations of total surplus, biodiversity, consumer surplus and producer surplus resulting from a shift from intensive to extensive farming.

Figure 7. Equilibrium with two outlets for the agricultural product, food and feed

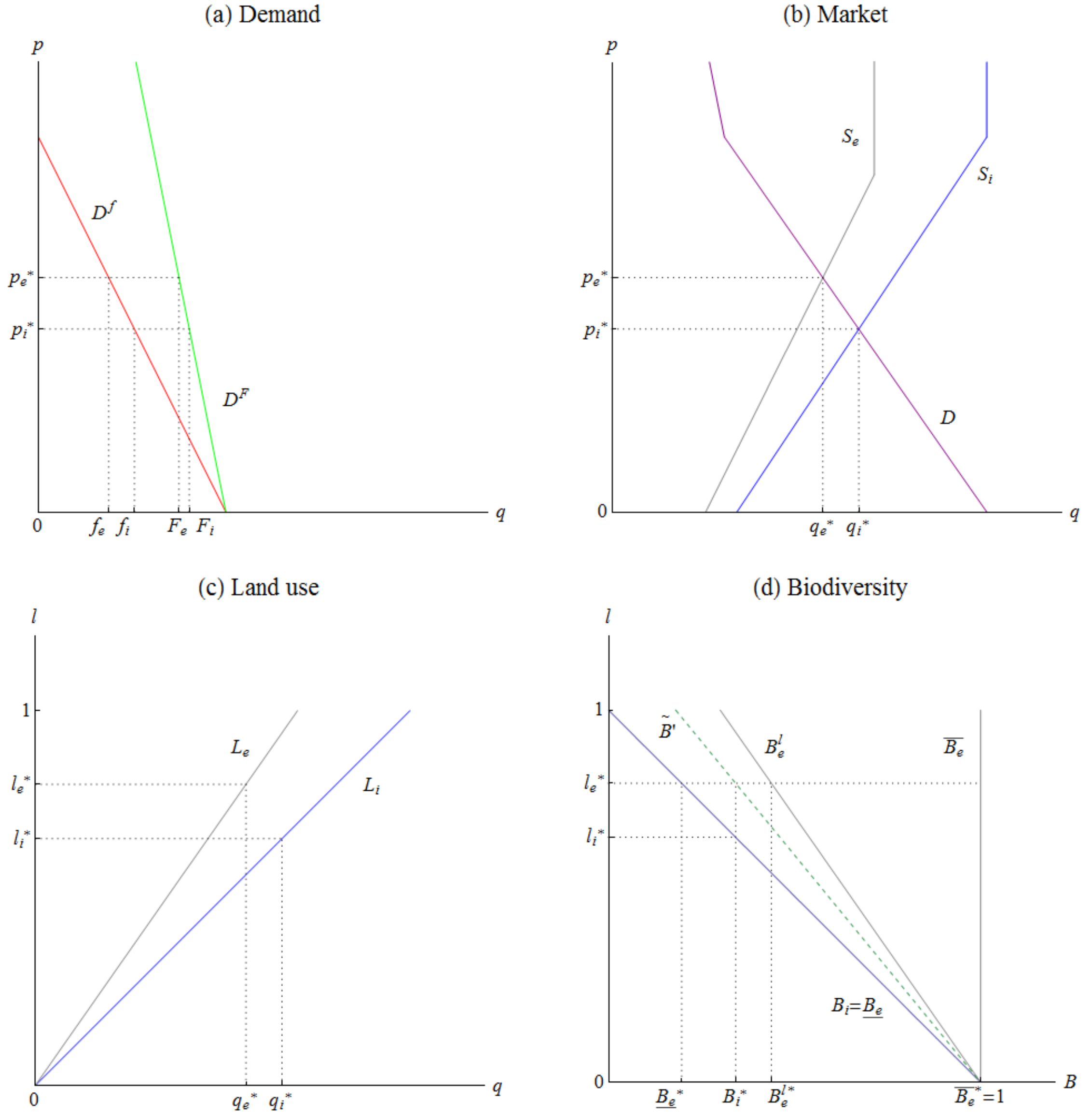


Figure 8. Equilibrium with biofuels as a third outlet for the agricultural product

(a) Demand (b) Market

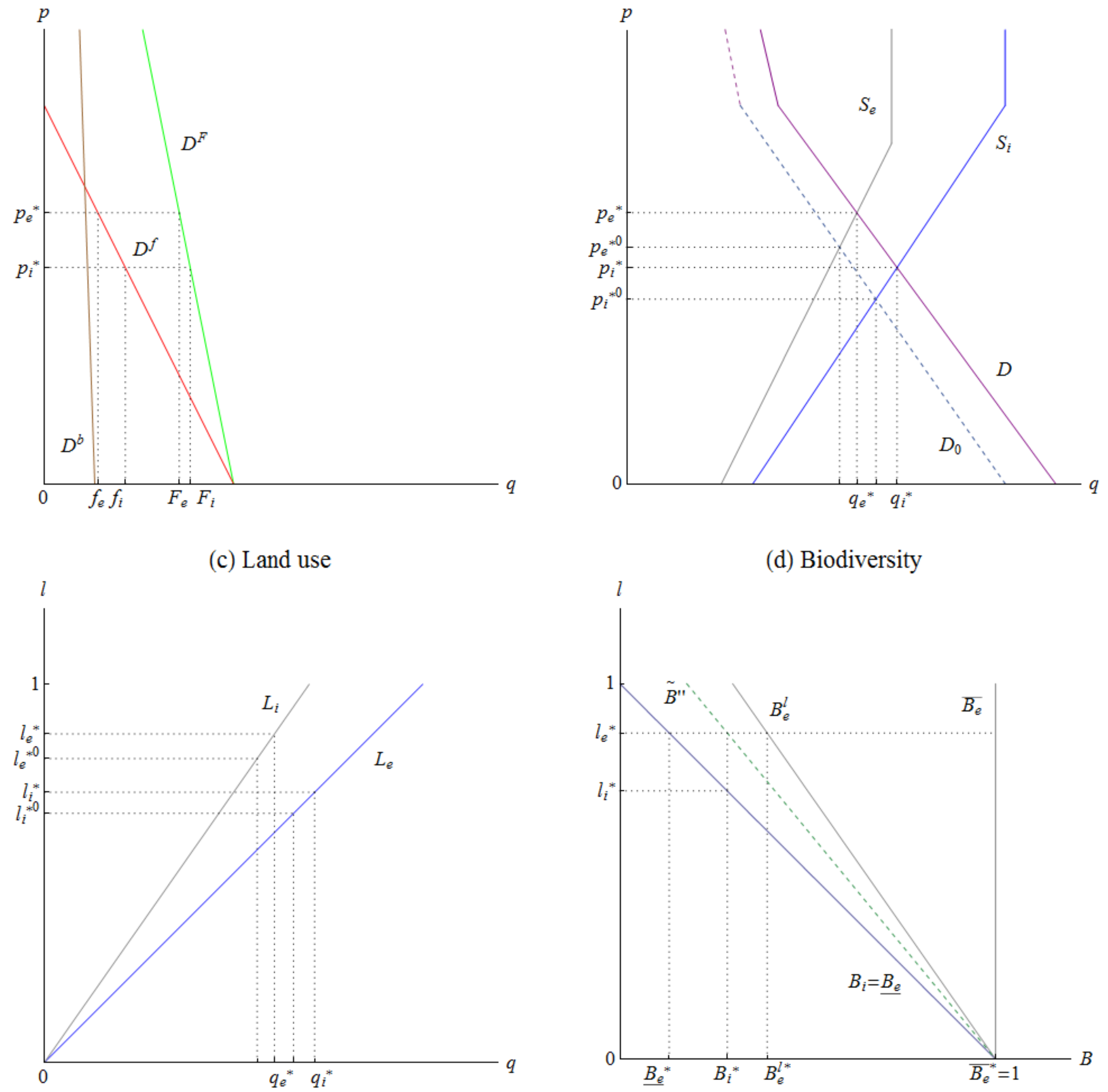
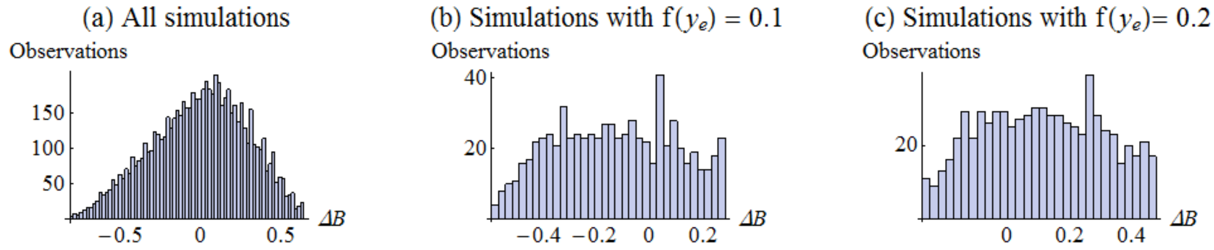
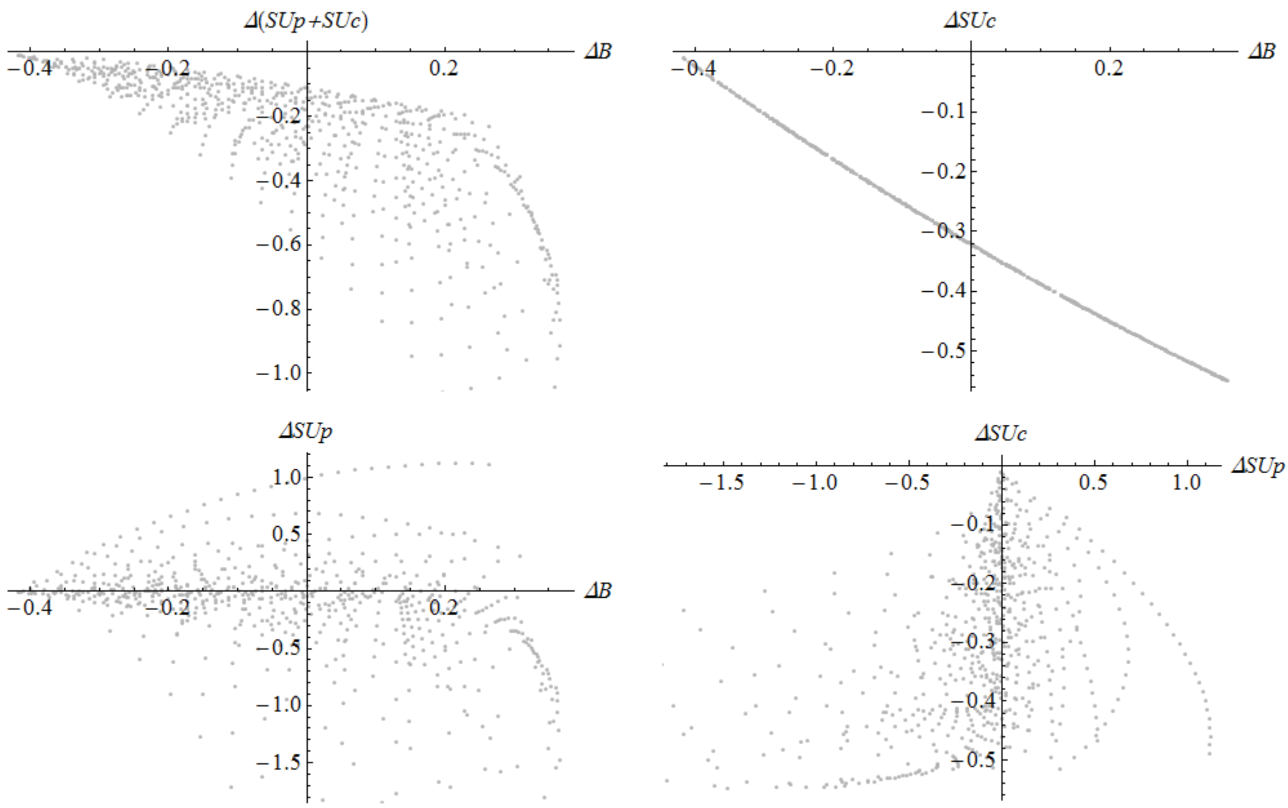


Figure A1. Effects on biodiversity of a shift from intensive to extensive farming with a parallel supply shift



Note: In this figure, ΔB represents the percentage variation in biodiversity resulting from a shift from intensive to extensive farming. Mean m and standard deviation s of the biodiversity change ΔB are: (a) in all simulations: m = - 1%, s = 30% ; (b) in simulations where $f(y_e)$ = 0.1 : m = - 13%, s = 22% ; (b) in simulations where $f(y_e)$ = 0.2 : m = 11%, s = 19%.

Figure A2. Welfare effects of a shift from intensive to extensive farming with a parallel supply shift ($f(y_e)$ = 0.15)



Note: same as figure 6.